Total Maximum Daily Loads for the Meadow River, Rockymarsh Run, and Warm Spring Run Watersheds, West Virginia

TECHNICAL REPORT

August 2016

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ACRONYMS AND ABBREVIATIONS

AMD	acid mine drainage
BOD	biochemical oxygen demand
CAIR	Clean Air Interstate Rule
DEM	Digital Elevation Model
DO	dissolved oxygen
DWWM	[WVDEP] Division of Water and Waste Management
GIS	geographic information system
HSPF	Hydrologic Simulation Program - FORTRAN
LA	load allocation
LSPC	Loading Simulation Program – C++
MDAS	Mining Data Analysis System
MOS	margin of safety
MS4	municipal separate storm sewer system
NHD	National Hydrography Dataset
NLCD	National Land Cover Dataset
NOAA-NCDC	National Oceanic and Atmospheric Administration, National Climatic Data Center
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
PET	potential evapotranspiration
POTW	publicly owned treatment works
TMDL	total maximum daily load
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WLA	wasteload allocation
WVDEP	West Virginia Department of Environmental Protection

1.0 INTRODUCTION

1.1 Purpose

The purpose of this document is to provide supplemental information regarding model selection, technical approaches, specific source representations and relevant supporting data to expand upon the TMDL report. The TMDL report provides a complete overview of the TMDL process, including stream impairment, pollutant sources, model calibration, baseline representations, allocation strategies, TMDLs, future growth provisions, reasonable assurance, implementation, and public comments.

Establishing the relationship between the instream water quality targets and source loads is a critical component of TMDL development. It allows for the evaluation of management options that will achieve the desired source load reductions. The link can be established through a range of techniques, from qualitative assumptions based on sound scientific principles to sophisticated computer modeling techniques. Ideally, the linkage is supported by monitoring data that allow the TMDL developer to associate certain waterbody responses with flow and loading conditions. This document presents the approaches taken to develop the linkage between sources and instream responses for TMDL development in West Virginia watersheds.

This document refers to supporting data organized into the following appendices:

Appendix A TMDL Work Load List
Appendix B Modeled Landuse
Appendix C Failing Septics
Appendix D NPDES Permits
Appendix E Hydrology & Water Quality Model Calibration
Appendix F Water Quality Data
Appendix G pH TMDL Modeling Approach for the Meadow River Watershed

1.2 Physical Considerations in Developing the TMDL Approach

The TMDL development approach must consider the dominant processes that affect pollutant loading and instream fate. The primary sources contributing to pH-and fecal coliform impairments include an array of point and nonpoint sources. Loading processes for nonpoint sources or land-based activities are typically rainfall-driven and thus relate to surface runoff and subsurface discharge to a stream. Permitted discharges might or might not be induced by rainfall, but they are represented by a known flow and concentration described in the permit limits.

Key instream factors that could be considered during TMDL development include routing of flow, and dilution. A significant instream process affecting the transport of fecal coliform bacteria is fecal coliform die-off.

Scale of analysis and waterbody type must also be considered when selecting the overall modeling approach. The approach should be able to evaluate watersheds of various sizes. The listed waters range from small headwater streams to large tributaries. Selection of scale should be sensitive to locations of key features, such as abandoned mines and point source discharges. At the larger watershed scale, land areas are aggregated into subwatersheds for practical representation of the system, commensurate with the available data. Occasionally, there are site-specific and localized acute problems that might require more detailed segmentation or definition of detailed modeling grids.

On the basis of the considerations described above, analysis of the monitoring data, review of the literature, and past metals, sediment, and fecal coliform bacteria modeling experience, the Mining Data Analysis System (MDAS) was chosen to represent the source-response linkage for pH and fecal coliform bacteria, when applicable in the streams included in this TMDL effort (See **Appendix A** for a complete list). The MDAS is a comprehensive data management and modeling system that is capable of representing loading from the nonpoint and point sources and simulating instream processes. The details of the MDAS model can be found in **Section 2.0**.

2.0 MINING DATA ANALYSIS SYSTEM

The MDAS was developed specifically for TMDL application in West Virginia to facilitate large scale, data intensive watershed modeling applications. The MDAS is particularly applicable to support TMDL development for areas affected by acid mine drainage (AMD) and other point and nonpoint pollution sources. A key advantage of the MDAS' development framework is that unlike Hydrologic Simulation Program–FORTRAN (HSPF), upon which it is based, it has no inherent limitations in terms of modeling size or upper limit of model operations and can be customized to fit West Virginia's individual TMDL development needs. The dynamic watershed model component within MDAS is the Loading Simulation Program–C++ (LSPC) (Shen, et al., 2002). The model simulates nonpoint source flow and pollutant loading as well as instream flow and pollutant transport, and is capable of representing time-variable point source contributions.

2.1 LSPC Water Quality Modeling Component

The LSPC model is the MDAS component that is most critical to TMDL development because it provides the linkage between source contributions and instream response. LSPC offers a number of key advantages over other modeling platforms, including:

- LSPC is able to simulate
  - A wide range of pollutants
  - Both rural and urban land uses
  - Both stream and lake processes
  - Both surface and subsurface impacts to flow and water quality
- The time-variable nature of the modeling enables a straightforward evaluation of the cause and effect relationship between source contributions and waterbody response, as well as direct comparison to relevant water quality criteria.
- The proposed modeling tools are free and publicly available. This is advantageous for distributing the model to interested stakeholders and amongst government agencies.

- LSPC provides storage of all modeling and point source permit data in a Microsoft Access database and text file formats to allow efficient manipulation of data.
- LSPC presents no inherent limitations regarding the size and number of watersheds and streams that can be modeled.
- LSPC provides post-processing and analytical tools designed specifically to support TMDL development and reporting requirements.
- A comprehensive modeling framework using the proposed LSPC approach facilitates development of TMDLs not only for this project, but also for potential future projects to address other impairments in the basin.

LSPC is a comprehensive watershed model used to simulate watershed hydrology and pollutant transport, as well as stream hydraulics and instream water quality. It is capable of simulating flow; the behavior of sediment, metals, nutrients, pesticides, and other conventional pollutants; temperature; and pH for pervious and impervious lands and for waterbodies. LSPC is essentially a recoded C++ version of selected HSPF modules. LSPC's algorithms are identical to HSPF's. The HSPF framework is developed in a modular fashion with many different components that can be assembled in different ways, depending on the objectives of the individual project. The model includes these major modules:

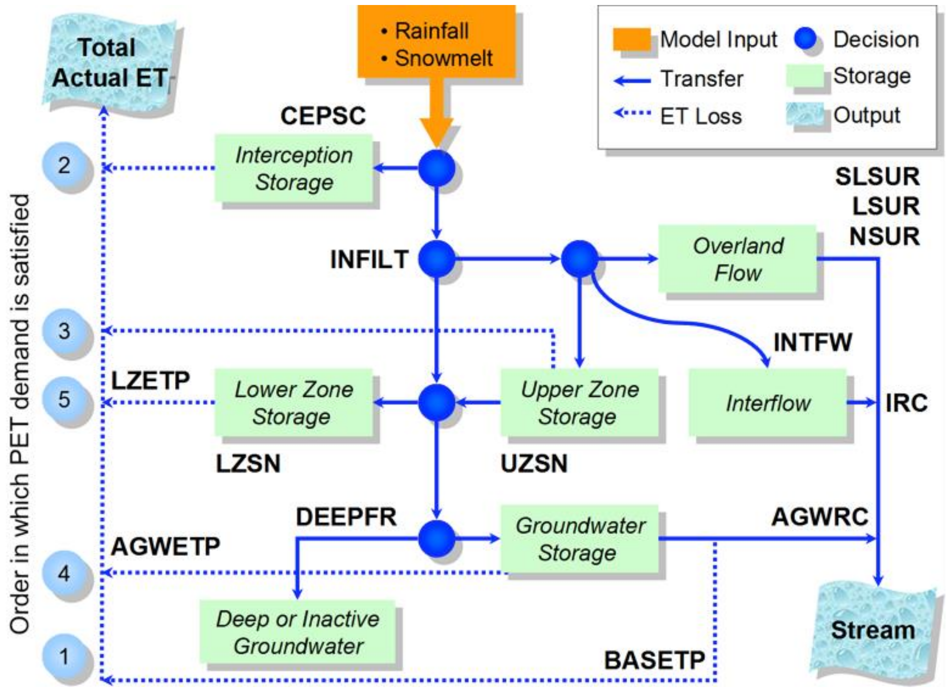
- PERLND - for simulating watershed processes on pervious land areas
- IMPLND - for simulating processes on impervious land areas
- SEDMNT - for simulating production and removal of sediment
- RCHRES - for simulating processes in streams and vertically mixed lakes
- SEDTRN - for simulating transport, deposition, and scour of sediment in streams

All of these modules include many submodules that calculate the various hydrologic, sediment, and water quality processes in the watershed. Many options are available for both simplified and complex process formulations. Spatially, the watershed is divided into a series of subbasins or subwatersheds representing the drainage areas that contribute to each of the stream reaches. These subwatersheds are then further subdivided into segments representing different land uses. For the developed areas, the land use segments are further divided into pervious and impervious fractions. The stream network links the surface runoff and subsurface flow contributions from each of the land segments and subwatersheds, and routes them through the waterbodies using storage-routing techniques. The stream-routing component considers direct precipitation and evaporation from the water surfaces, as well as flow contributions from the watershed, tributaries, and upstream stream reaches. Flow withdrawals and diversions can also be accommodated.

The stream network is constructed to represent all the major tributary streams, as well as different portions of stream reaches where significant changes in water quality occur. Like the watershed components, several options are available for simulating water quality in the receiving waters. The simpler options consider transport through the waterways and represent all transformations and removal processes using simple, first-order decay approaches. Decay may be used to represent the net loss due to processes like settling and adsorption.

2.1.1 The Hydrologic Cycle in LSPC.

The hydrologic (water budget) process in LSPC is a fairly comprehensive representation of the natural hydrological cycle. Rainfall or snowmelt is routed to constructed landscapes, vegetation, and/or soil. Varying soil types, which depend on model parameterization by land use, allow the water to infiltrate at different rates, while evaporation and plant matter exert a demand on available water. Water flows overland and through the soil matrix. The vertical land profile in the LSPC model environment is represented by three significant flow paths: surface, interflow, and groundwater outflow. The parameters associated with various stages of the LSPC water budget are shown schematically in **Figure 2-1**.



Key to Parameters- Listed in Order as they appear on diagram.

ET is the evapotranspiration.	CEPSC is the interception storage capacity.
SLSUR is the overland flow slope.	INFILT is the index to the infiltration capacity of the soil.
LSUR is the surface runoff length.	NSUR is the Manning's *n* for the assumed overland flow plane.
LZETP is the lower zone ET parameter.	LZSN is the lower nominal moisture.
UZSN is the upper nominal storage.	INTFW is the interflow inflow.
IRC is the interflow recession.	AGWETP is the active groundwater ET
DEEPFR is the fraction to deep GW.	AGWRC is the base groundwater recession.
BASETP is the baseflow ET parameter.	

Figure 2-1. Water Budget Schematic illustrating order in which the potential evapotranspiration (PET) is satisfied in the LSPC model.

2.1.3 Water Quality

The GQUAL module in LSPC is generalized enough to represent any pollutant from the land surface. In addition to surface accumulation and wash-off processes, different concentrations can be associated with interflow and baseflow hydrology. The fate and transport of GQUAL constituents can also be modeled using temperature-dependent first order decay or sediment-associated sorption/desorption of dissolved or particulate pollutant forms. This flexibility allows a wide range of general pollutants to be modeled, including bacteria, metals, nutrients and other toxics.

LSPC also offers the reach quality (RQUAL) module from HSPF, which addresses the fate, transport, and transformation of nutrient species in the water column. RQUAL includes routines for modeling ammonia volatilization, nitrification/denitrification, and adsorption/desorption of nutrients during transport. Depending on the requirements of the natural system under consideration, the model can also simulate interaction of nutrients with phytoplankton, impact to in-stream biochemical oxygen demand (BOD), and dissolved oxygen levels.

As will be discussed, the MDAS enhances LSPC by adding specialized chemical loadings and reactive transport capabilities to permit the modeling of complex and comprehensive chemical processes that are not available in the current LSPC or HSPF, including thermodynamics-based chemical reactions and additional integrated chemical kinetics.

2.2 Mining Data Analysis System (MDAS) Model Configuration

The MDAS was configured for all watersheds, and LSPC was used to simulate each of the watersheds as a series of hydrologically connected subwatersheds. Configuration of the model involved subdividing each large watershed into modeling units and performing continuous simulation of flow and water quality for these units using meteorological, landuse, point source loading, and stream data. The specific pollutants simulated were pH and fecal coliform bacteria. This section describes the configuration process and key components of the model in greater detail.

2.2.1 Watershed Subdivision

To represent watershed loadings and the resulting concentrations of pollutants of concern, each watershed was divided into hydrologically connected subwatersheds. These subwatersheds represent hydrologic boundaries. The division was based on elevation data (7.5-minute Digital Elevation Model [DEM] from the U.S. Geological Survey [USGS]), stream connectivity (from USGS's National Hydrography Dataset [NHD] stream coverage), the impairment status of tributaries, and the locations of monitoring stations. This delineation enabled the evaluation of water quality and flow at impaired water quality stations, and it allowed management and load reduction alternatives to be varied by subwatershed.

2.2.2 Meteorological Data

Meteorological data are a critical component of the watershed model. Appropriate representation of precipitation, wind speed, potential evapotranspiration, cloud cover, temperature, and dew point is required to develop a valid model. Meteorological data were obtained from a number of weather stations in an effort to develop the most representative dataset for each watershed. The meteorological data was represented using two different methodologies in the development of TMDLs in Meadow River, Rockymarsh Run and Warm Spring Run Watersheds.

Rockymarsh Run and Warm Spring Run Watersheds

In general, hourly precipitation data are recommended for nonpoint source modeling. Therefore, only weather stations with hourly recorded data were considered in developing a representative dataset. Long-term hourly precipitation data available from the National Oceanic and Atmospheric Administration National Climatic Data Center (NOAA-NCDC) weather stations were used. The remaining required meteorological data (wind speed, potential evapotranspiration, cloud cover, temperature, and dew point) were also available from NOAA-NCDC weather stations. The data were applied to each subwatershed in the Rockymarsh Run and Warm Spring Run Watersheds according to proximity to the weather station.

Meadow River Watershed

Appropriate spatial resolution of weather data is also important when modeling the hydrology of mountainous watersheds in West Virginia where abrupt changes in topography are common between mountains and valleys. Two grid-based data products were used to develop model weather input files with appropriate spatial and temporal resolution for the Meadow River Watershed. The Parameter-Elevation Regressions on Independent Slopes Model (PRISM) and the North American Land Data Assimilation System (NLDAS-2) are both publicly available weather datasets. They can be used separately or together to generate comprehensive weather input files at a fine spatial resolution.

The PRISM dataset was developed by Oregon State University's PRISM Climate Group. The PRISM dataset provides daily, monthly, yearly, and single-event gridded data products of mean temperature and precipitation, and max/min temperatures. PRISM uses a combination of climatologically-aided interpolation (CAI) and Radar (National Weather Service Stage 2 unbiased). The dataset uses a robust network of weather station point measurements incorporated into the PRISM statistical mapping system (PRISM Climate Group, 2014). PRISM products use a weighted regression scheme to account for complex climate regimes associated with orography, rain shadows, temperature inversions, slope aspect, coastal proximity, and other factors. PRISM data features daily weather on 4 km grid spatial scale.

The NLDAS-2 dataset is maintained through a partnership between the National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and several large universities (Cosgrove et al., 2003). It combines rain gauge data with Radar observations to predict hourly weather parameters such as precipitation, solar radiation, wind, and humidity. NLDAS-2 data has hourly weather on a 12 km grid scale.

NLDAS-2 and PRISM datasets are broadly used by various user communities in modeling, research, and applications (NCAR, 2013). PRISM was chosen for TMDL modeling purposes because it featured a higher spatial resolution than NLDAS-2. However, hourly precipitation from the NLDAS-2 dataset was also extracted and used along with supporting data from NOAA National Climatic Data Center (NCDC) Surface Airways Stations to manipulate the daily PRISM weather data into hourly model input files.

PRISM daily time series data was downloaded at 2.5 arc minutes (~4 km) resolution from the PRISM website. Precipitation and max/min temperature data for each grid cell that intersected with TMDL watersheds were identified and processed to create a time series for each 4 km x 4 km grid cell. Once the precipitation and temperature time series for the PRISM grid cell files were created, a weather input file was developed for each grid cell. Given that slight variability was observed between the grid cells at the12-digit Hydrologic Unit Code (HUC) scale and in order to allow more feasibility when executing the models, one centrally located weather input file per HUC was identified as representative of the weather in the area. Model subwatersheds falling within each 12-digit HUC were then assigned the appropriate weather input file for hydrologic modeling purposes.

In certain environments, snowfall and snowmelt have a dominant impact on hydrology and associated water quality. LSPC uses the energy balance method to simulate snow behavior. In addition to precipitation inputs, the energy balance requires temperature, dew point temperature, wind speed, and solar radiation as meteorological drivers. The SNOW module uses the meteorological information to determine whether precipitation falls as rain or snow, how long the snowpack remains, and when snowpack melting occurs. Heat is transferred into or out of the snowpack through net radiation heat, convection of sensible heat from the air, latent heat transfer by moist air condensation on the snowpack, rain, and conduction from the ground beneath the snowpack. The snowpack essentially acts like a reservoir that has specific thermodynamic rules for how water is released. Melting occurs when the liquid portion of the snowpack exceeds the snowpack's holding capacity; melted snow is added to the hydrologic cycle (**Figure 2-2** is a schematic of the snow process in LSPC).

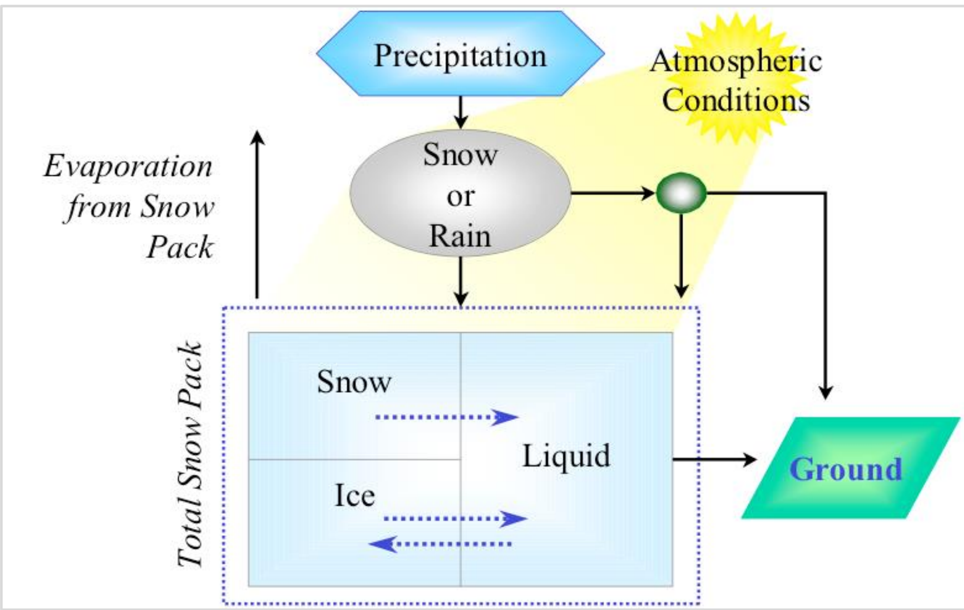


Figure 2-2. Snow Simulation Schematic

2.2.3 Stream Representation

Modeling subwatersheds and calibrating hydrologic and water quality model components require routing flow and pollutants through streams and then comparing the modeled flows and concentrations with available data. In the MDAS model, each subwatershed was represented by a single stream segment, which was identified using the USGS NHD stream coverage.

To route flow and pollutants, rating curves were developed for each stream using Manning's equation and representative stream data. Required stream data include slope, Manning's roughness coefficient, and stream dimensions, including mean depths and channel widths. Manning's roughness coefficient was assumed to be 0.02 (representative of natural streams) for all streams. Slopes were calculated based on DEM data and stream lengths measured from the NHD stream coverage. Stream dimensions were estimated using regression curves that related upstream drainage area to stream dimensions (Rosgen, 1996).

2.2.4 Hydrologic Representation

Hydrologic processes were represented in the MDAS using algorithms from two HSPF modules: PWATER (water budget simulation for pervious land segments) and IWATER (water budget simulation for impervious land segments) (Bicknell et al., 1996). Parameters associated with infiltration, groundwater flow, and overland flow were designated during model calibration.

2.2.5 Pollutant Representation

The loading contributions of pollutants from different nonpoint sources were represented in MDAS using the PQUAL (simulation of quality constituents for pervious land segments) and IQUAL (simulation of quality constituents for impervious land segments) modules of HSPF (Bicknell et al., 1996). Pollutant transport was represented in the streams using the GQUAL (simulation of behavior of a generalized quality constituent) module. Additionally, the enhanced MDAS capability provides thermodynamic-based, time-variable chemical loadings and reactive transport model within the streams.

3.0 MDAS FECAL COLIFORM

Watersheds with varied landuses, dry- and wet-period loads, and numerous potential sources of pollutants typically require a model to ascertain the effect of source loadings on instream water quality. This relationship must be understood to develop a TMDL that addresses a water quality standard, as well as an effective implementation plan. In this section, the modeling techniques that were applied to simulate fecal coliform bacteria fate and transport are discussed.

3.1 Fecal Coliform Nonpoint Sources

To explicitly model non-permitted (nonpoint) sources of fecal coliform bacteria, the existing NLCD 2011 landuse categories were consolidated to create model landuse groupings, as shown in **Table 3-1**. Modeled landuses contributing to bacteria loads include pasture, cropland, urban pervious lands, urban impervious lands, forest, barren land, and wetlands. The modeled landuse coverage provided the basis for estimating and distributing fecal coliform bacteria loadings associated with conventional landuses. Subwatershed-specific details of the modeled landuses are shown in **Appendix B**.

Residential/urban lands contribute fecal coliform loads to the receiving streams through the wash-off of bacteria that build up in industrial areas, on paved roads, and in other residential/urban areas because of human activities. These contributions differ, based on the perviousness of the land. For example, the transport of the bacteria loads from impervious surfaces is faster and more efficient, whereas the accumulation of bacteria loads on pervious areas is expected to be higher (because pets spend more time on grass). Therefore, residential/urban lands were divided into two categories—residential/urban pervious and residential/urban impervious. Percent impervious estimates for the residential/urban landuse categories were used to calculate the total area of impervious residential/urban land in each subwatershed. The percent pervious/impervious assumptions for residential/urban land categories are shown in **Table 3-2.**

Table 3-1. Fecal coliform bacteria model landuse grouping

Model Category	NLCD 2011 Category
Barren	Barren Land (Rock/Sand/Clay)
Cropland	Cultivated Crops
Forest	Deciduous Forest
	Evergreen Forest
	Mixed Forest
	Dwarf Scrub
	Shrub/Scrub
Pasture and Riparian Pasture	Grassland/Herbaceous
	Pasture/Hay
Residential/Urban Impervious (See **Table 3-2**)	Developed, Open Space
	Developed, Low Intensity
	Developed, Medium Intensity
	Developed, High Intensity
Residential/Urban Pervious (See **Table 3-2**)	Developed, Open Space
	Developed, Low Intensity
	Developed, Medium Intensity
	Developed, High Intensity
Water	Open Water
Wetlands	Palustrine Forested Wetland
	Palustrine Scrub/Shrub Wetland
	Emergent Herbaceous Wetland

Table 3-2. Average percentage of pervious and impervious land for NLCD 2011 residential/urban landuse types

Landuse	Pervious (%)	Impervious (%)
Developed, Open Space	85	15
Developed, Low Intensity	65	35
Developed, Medium Intensity	35	65
Developed, High Intensity	10	90

3.1.1 Wildlife

Frequently, nonpoint sources are characterized by build-up and wash-off processes. On the land surface, fecal coliform bacteria accumulate over time and wash off during rain events. As the runoff transports the sediment over the land surface, more fecal coliform bacteria are collected and carried to the stream. While the concentrations of bacteria are increasing, some bacteria are also dying. The net loading into the stream is determined by the local watershed hydrology. Fecal coliform accumulation rates (in number per acre per day) can be calculated for each landuse based on all sources contributing fecal coliform bacteria to the land surface.

Landuses that experience bacteria accumulation due to wildlife include the following: wetlands, forest, grassland, shrubland, and barren. Accumulation rates for fecal coliform bacteria in forested areas were developed using reference numbers from past TMDLs, incorporating wildlife estimates obtained from West Virginia's Division of Natural Resources (WVDNR). In addition, WVDEP conducted storm sampling on a 100 percent forested subwatershed (Shrewsbury Hollow) within the Kanawha State Forest, Kanawha County, West Virginia to determine wildlife contributions of fecal coliform. These results were used during the model calibration process. On the basis of the low fecal accumulation rates for forested areas, the stormwater sampling results, and model simulations, wildlife is considered to be a natural "background" source of fecal coliform bacteria that does not alone cause violations of the state water quality criteria. For this reason, TMDL reductions are not prescribed for wildlife sources.

3.1.2 Agriculture

Pasture and cropland landuses accumulate bacteria when livestock are present, or when manure is applied as fertilizer. Modelers used storm sampling data, literature values, and previous fecal coliform TMDLs to develop initial fecal coliform bacteria loading rates for the model (Miertschin, 2006). However, these initial estimates did not apply uniformly to the entire watershed area being modeled. To accommodate this variation, the fecal coliform modeling parameters for bacterial build-up and accumulation limit were fine-tuned during model calibration to produce model output that more closely matched available pre-TMDL stream monitoring data.

Agricultural runoff potential was assessed by WVDEP during source tracking efforts. Pastures were categorized into four general types of runoff potential: high, moderate, low or negligible. In general, pastures with steeper slopes and livestock with stream access or close proximity to the stream channel received a high runoff potential assessment. Pastures in areas with gentle slopes, without livestock stream access, with greater distance to a stream, or where streams contained well-established riparian buffers received a low or negligible runoff potential. Fecal coliform build-up and accumulation limit parameters in areas rated as high or moderate with respect to runoff potential were assigned higher values; pastures with low or negligible runoff potential were assigned values slightly above natural background conditions.

3.1.3 Residential/Urban Runoff

Sources of fecal coliform bacteria in residential/urban areas include wildlife and pets, particularly dogs. Much of the loading from urban areas is due to the greater amount of impervious area relative to other landuses, and the resulting increase in runoff. In estimating the potential loading of fecal coliform bacteria from residential/urban areas, accumulation rates are often used to represent the aggregate of available sources.

Residential/urban lands contribute nonpoint source fecal coliform bacteria loads to receiving streams through the wash-off of fecal coliform bacteria that build up on both pervious and impervious surfaces in industrial areas, on paved roads, and in residential areas (from failing septic systems, straight pipes contributing raw sewage, and wildlife). Residential/urban areas were consolidated into two landuse categories—residential/urban pervious and residential/urban impervious.

3.1.4 Failing Septic Systems

Failing septic systems represent non-permitted (nonpoint) sources that can contribute fecal coliform to receiving waterbodies through surface or subsurface flow. Although categorized as nonpoint sources (part of the load allocation in the TMDL equation), for modeling purposes it was most practical to model failing septic systems as continuous flow sources in the MDAS. To calculate source loads, values for both wastewater flow and fecal coliform concentration were needed. Literature values for failing septic system flows and fecal concentrations vary over several orders of magnitude. Therefore it was necessary to perform original analysis using West Virginia pre-TMDL monitoring and source tracking data.

To calculate failing septic wastewater flows, TMDL watersheds were divided into four septic failure zones during the source tracking process. Septic failure zones were delineated by geology, and defined by rates of septic system failure. Two types of failure were considered: complete failure and periodic failure. For the purposes of this analysis, complete failure was defined as 50 gallons per house per day of untreated sewage escaping a septic system as overland flow to receiving waters. Periodic failure was defined as 25 gallons per house per day of untreated sewage escaping a septic system as overland flow to receiving waters. Both types of failure were modeled as daily, year-round flows to simplify calculations. **Table 3-3** shows the percentage of homes with septic systems in each of the four septic zones experiencing septic system failure.

Table 3-3. Septic failure rates in septic failure zones

Type	Zone			
	Very Low	Low	Medium	High
Percent Homes with Periodic Failure	3%	7%	13%	19%
Percent Homes with Complete Failure	5%	10%	24%	28%

GIS shapefiles identifying the location of public sewer systems were used to identify sewered areas in the watersheds. GIS shapefiles developed to track all addressable structures in West Virginia for 911 emergency purposes were used to determine the locations of structures with potentially failing septic systems in the fecal coliform TMDL watersheds. In the first step of the analysis, structures falling within known sewered areas were excluded from further consideration. Second, homes located more than 100 meters from a stream were excluded and not considered significant potential sources of fecal coliform because of the natural attenuation of fecal coliform concentrations that occurs because of bacterial die-off during overland travel (Walsh and Kunapo, 2009). Estimated septic system failure rates across the watershed range from three percent to 28 percent. The remaining structures were assigned to the TMDL modeled subwatersheds they fell within. These structures were further stratified by geographic zones of septic failure based on soil characteristics and geology. Frequently, subwatersheds had area straddling more than one failing septic zone. Using GIS techniques, each structure was identified both by subwatershed and failing septic zone.

Under WVDEP guidance, it was assumed that 54 percent of the non-sewered structures in each subwatershed were inhabited homes with septic systems. Septic failure rates were applied to the assumed homes with septic systems in each modeled subwatershed. Once those proportions of complete and seasonal failure were applied, failing septic wastewater flow was calculated by subwatershed using the periodic and seasonal flow rates of 50 gallons per house per day for complete failure, and 25 gallons per house per day for periodic failure. For modeling purposes, failing septic system flows from multiple houses were totaled and incorporated into the model as a single continuous flow source for each subwatershed.

Once failing septic flows had been modeled, an appropriate fecal coliform concentration was determined at the TMDL watershed scale. Based on past experience with other West Virginia TMDLs, a base concentration of 10,000 counts per 100 mL was used as a beginning concentration for failing septics. This concentration was further refined during model calibration at the subwatershed scale. A sensitivity analysis was performed by varying the modeled failing septic concentrations in multiple model runs, and then comparing model output to pre-TMDL monitoring data. The failing septic analyses are presented in **Appendix C**.

3.2 Fecal Coliform Point Sources

The most prevalent fecal coliform point sources are the permitted discharges from sewage treatment plants. All treatment plants are regulated by NPDES permits that require effluent disinfection and compliance with strict fecal coliform limitations (200 counts/100 milliliters [monthly geometric mean] and 400 counts/100 mL [maximum daily]). However, noncompliant discharges and collection system overflows can contribute loadings of fecal coliform bacteria to receiving streams. When present within the watersheds, the following types of fecal coliform permitted/point sources were represented in the model:

- Individual POTWs discharge treated effluent at one or more outlets
- Privately owned sewage treatment plants operating under individual NPDES permits discharges at one or more outlets
- Package plants operating under general permits
- Home aeration units operating under “HAU” general permits.

The various sewage treatment plant effluents were represented in the model by their permitted design flows and the monthly geometric mean fecal coliform effluent limitation of 200 counts/100 mL. See **Appendix D** for a complete listing of NPDES permits.

3.2.2 Municipal Separate Storm Sewer Systems (MS4)

Runoff from residential and urbanized areas during storm events can be a significant fecal coliform source. USEPA’s stormwater permitting regulations require public entities to obtain NPDES permit coverage for stormwater discharges from municipal separate storm sewer systems (MS4s) in specified urbanized areas. As such, MS4 stormwater discharges are considered point sources and are prescribed WLAs.

MS4 source representation was based upon precipitation and runoff from landuses determined from the modified NLCD 2011 landuse data, the jurisdictional boundary of the cities, and the transportation-related drainage areas for which DOH has MS4 responsibility. WVDEP consulted with local governments and obtained information to determine drainage areas to the respective systems and best represent MS4 pollutant loadings.

4.0 MDAS MODEL CALIBRATION

After the various models were configured, calibration was performed at multiple locations in each watershed. Calibration refers to the adjustment or fine-tuning of modeling parameters to reproduce observations. Model calibration focused on two main areas: hydrology and water quality. Upon completion of the calibration at selected locations, the calibrated dataset containing parameter values for modeled sources and pollutants was complete. This dataset was applied to areas for which calibration data were not available.

4.1 Hydrology Calibration

This section describes the modeling and calibration of the snow and hydrology components of the watershed model. Simulation of hydrologic processes is an integral part of the development of an effective watershed model. The goal of the calibration was to obtain physically realistic model prediction by selecting parameter values that reflect the unique characteristics of the watershed. Spatial and temporal aspects were evaluated through the calibration process.

Hydrologic calibration was performed after configuring the model. For the MDAS, calibration is an iterative procedure of parameter evaluation and refinement as a result of comparing simulated and observed values of interest. It is required for parameters that cannot be deterministically and uniquely evaluated from topographic, climatic, physical, and chemical characteristics of the watershed and compounds of interest. Hydrology calibration was based on several years of simulation to evaluate parameters under a variety of climatic conditions. The calibration procedure resulted in parameter values that produce the best overall agreement between simulated and observed stream flow values throughout the calibration period. Calibration included a time series comparison of daily, monthly, seasonal, and annual values, and individual storm events. Composite comparisons (e.g., average monthly stream flow values over the period of record) were also made. All of these comparisons must be evaluated for a proper calibration of hydrologic parameters.

The MDAS hydrology algorithm follows a strict conservation of mass, with various compartments available to represent different aspects of the hydrologic cycle. Sources of water are direct rainfall or snowmelt. Potential sinks from a land segment are total evapotranspiration, flow to deep groundwater aquifers, and outflow to a reach. From the reach perspective, sources include land outflow (runoff and baseflow), direct discharges, precipitation, or flow routed from upstream reaches. Sinks include surface evaporation, mechanical withdrawals, or reach outflow.

4.1.1 Snow

The method used to simulate snow behavior was the energy balance approach. The MDAS SNOW module uses the meteorological forcing information to determine whether precipitation falls as rain or snow, how long the snowpack remains, and when snowpack melting occurs. Heat is transferred into or out of the snowpack through net radiation heat, convection of sensible heat from the air, latent heat transfer by moist air condensation on the snowpack, from rain, and through conduction from the ground beneath the snowpack. Melting occurs when the liquid portion of the snowpack exceeds its holding capacity; melted snow is added to the hydrologic cycle.

4.1.2 Surface Hydrology

As mentioned earlier, the MDAS hydrology algorithms follow a strict conservation of mass. The source of water to the land is either direct precipitation or snowmelt. Some of this water is intercepted by vegetation or by other means. The interception is represented in the model by a “bucket” that must be filled before any excess water is allowed to reach the land surface. The size, in terms of inches per unit of area, of this “bucket” can be varied monthly to represent the level of each compartment (both above and below the land surface).

Water that is not intercepted is placed in surface detention storage. If the land segment is impervious, no subsurface processes are modeled, and the only pathway to the stream reach is through surface runoff. If the land segment is pervious, the water in the surface detention storage can infiltrate, be categorized as potential direct runoff, or be divided between the two depending on a function of the soil moisture and infiltration rate. The water that is categorized as potential direct runoff is partitioned into surface storage/runoff, interflow, or kept in the upper zone storage. Surface runoff that flows out of the land segment depends on the land slope and roughness, and the distance it has to travel to a stream. Interflow outflow recedes based on a user-defined parameter.

Water that does not become runoff, interflow, or lost to evaporation from the upper zone storage will infiltrate. This water will become part of the lower zone storage, active groundwater storage or be lost to the deep/inactive groundwater. The lower zone storage acts like a “container” of the subsurface. This “container” needs to be full in order for water to reach the groundwater storage. Groundwater is stored and released based on the specified groundwater recession, which can be made to vary non-linearly.

The model attempts to meet the evapotranspiration demand by evaporation of water from baseflow (groundwater seepage into the stream channel), interception storage, upper zone storage, active groundwater, and lower zone storage. How much of the evapotranspiration demand is allowed to be met from the lower zone storage is determined by a monthly variable parameter. Finally, water can exit the system in three ways: evapotranspiration, deep/inactive groundwater, or entering the stream channel. The water that enters the stream channel can come from direct overland runoff, interflow outflow, and groundwater outflow.

Some of the hydrologic parameters can be estimated from measured properties of the watersheds while others must be estimated by calibration. Model parameters adjusted during calibration are associated with evapotranspiration, infiltration, upper and lower zone storages, recession rates of baseflow and interflow, and losses to the deep groundwater system. During hydrology calibration, land segment hydrology parameters were adjusted to achieve agreement between daily average simulated and observed stream flow at selected locations throughout the basin.

As a starting point, many of the hydrology calibration parameters originated from the USGS Scientific Investigations Report 2005-5099 (Atkins et al., 2005). During calibration, agreement between observed and simulated stream flow data was evaluated on an annual, seasonal, and daily basis using quantitative as well as qualitative measures. Specifically, annual water balance, groundwater volumes and recession rates, surface runoff and interflow volumes and timing were evaluated. Calibration of the hydrologic model was accomplished by first adjusting model parameters until the simulated and observed annual and seasonal water budgets matched. Then, the intensity and arrival time of individual events was calibrated. This iterative process was repeated until the simulated results closely represented the system and reproduced observed flow patterns and magnitudes. The model calibration was performed using the guidance of error statistics criteria specified in HSPEXP (Lumb et al., 1994). Output comparisons included: mean runoff volume for simulation period, monthly runoff volumes, daily flow time series, and flow frequency curves, among others. The flow-frequency curves and temporal analyses are presented in **Appendix E**.

The hydrology calibration statistics for the flow gage on the Meadow River are shown in **Table 4-1**. A graphical representation of hydrology calibration results is presented in **Error! Reference source not found.** Refer to **Appendix E** for additional calibration results.

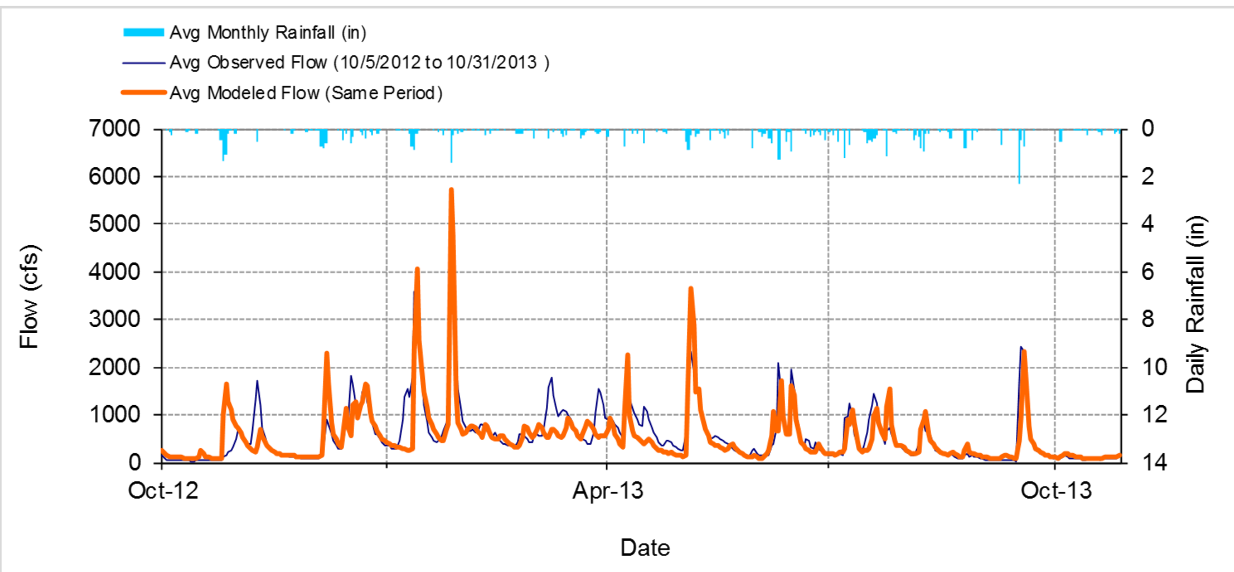


Figure 4-1. Comparison of simulated and observed flow from October 2012 to October 2013 for subwatershed 153 vs. USGS 03190000 Meadow River at Nallen, WV

Table 4-1. Comparison of simulated and observed flow from October 2012 to October 2013 (USGS station ID number 03190000 Meadow River at Nallen, WV)

Simulated versus Observed Flow	Percent Error	Recommended Criterion[a]
Error in total volume:	-7.75	10
Error in 50% lowest flows:	5.77	10
Error in 10% highest flows:	-5.00	15
Seasonal volume error - summer:	-3.70	30
Seasonal volume error - fall:	17.39	30
Seasonal volume error - winter:	-12.51	30

Seasonal volume error - spring:	-18.98	30
Error in storm volumes:	-4.97	20
Error in summer storm volumes:	-13.05	50

4.2 Fecal Water Quality Calibration

For fecal coliform model water quality calibration, fecal coliform build-up and limit parameters specific to modeled landuses were adjusted to calibrate the model. Prior to TMDL development, WVDEP collected comprehensive and pollutant source water quality data, which are used as observed data during water quality calibration. The comprehensive monitoring data are summarized in **Appendix F**. Modeled fecal coliform concentrations from failing septic systems were adjusted to best represent fecal loading in impaired streams. Results from fecal coliform water quality calibration are also presented in **Appendix E.**

5.0 MDAS pH

To appropriately address pH TMDLs for impaired watersheds, it was necessary to apply an MDAS model capable of representing instream chemical reactions coupled with upland chemical mass loadings

In the Meadow River watershed, observed in-stream low pH most likely originates from atmospheric deposition of strong acid anions acidifying soils and water. In addition to the land-based source loadings, instream chemical reactions also influence stream water quality. Chemical equilibrium, reaction time scales, and kinetics of the chemical reactions must be considered to evaluate the fate and transport of chemical constituents. It is critical for the model to incorporate reactive transport capability with both thermodynamics and chemical kinetics to assess instream water quality conditions. Detailed assessments of individual subwatershed physical and chemical characteristics and calibration results, as well as a discussion of the atmospheric deposition module linkage to MDAS are provided in **Appendix G**. The remainder of this section describes the MDAS model functionality and source representation as it relates to pH simulation.

5.1 Overview of the MDAS pH Model

The MDAS model includes a comprehensive watershed hydrology and source loading functionality with one-dimensional reactive chemical transport capability. The reactive chemical transport code is derived from USEPA's Metal Equilibrium Speciation Model (MINTEQA2; Allison et al.1991). The equilibrium computational code for ionic speciation of cationic and anionic components in aqueous systems originates from the Massachusetts Institute of Technology's Chemical Equilibrium Model (MINEQL; Westall et al. 1986, 1974). The non-equilibrium/kinetic reactions concepts are either from chemical kinetics of USGS's pH-Redox-Equilibrium-Equations in C Model (PHREEQC model; Parkhurst and Appelo, 2002) or published chemical kinetic reactions. The chemical reaction modules in MDAS are seamlessly linked with all of the capabilities of the LSPC model to predict chemical fate/transport on a basin scale. Both the LSPC and aqueous speciation models that are the basis of MDAS have been described in detail in USEPA (2009), Allison et al. (1991) and Westall (1986 and 1974).

5.2 Overview of Land Components of the pH MDAS Model

Three potential chemical loading sources can be simulated at the modeled land surface in MDAS: atmospheric deposition, potential anthropogenic input, and existing chemical components (background) on the land associated with either natural or anthropogenic origins.

Acid rain is produced when atmospheric moisture reacts with gases to form sulfuric acid, nitric acid, and carbonic acid. These gases are primarily formed from nitrogen dioxides and sulfur dioxide, which enter the atmosphere through exhaust and smoke from burning fossil fuels such as gas, oil, and coal. Two-thirds of sulfur dioxides and one-fourth of nitrogen oxides present in the atmosphere are attributed to fossil fuel burning electric power generating plants (USEPA, 2005a). Acid rain crosses watershed boundaries and may originate in the Ohio River valley or the Midwest.

The majority of the acid deposition occurs in the eastern United States. In March 2005, the USEPA issued the Clean Air Interstate Rule (CAIR), which places caps on emissions for sulfur dioxide and nitrogen dioxides for the eastern United States. It is expected that CAIR will reduce sulfur dioxide emissions by over 70 percent and nitrogen oxides emissions by over 60 percent from the 2003 emission levels (USEPA, 2005b). Since the pollution is highly mobile in the atmosphere, reductions based on CAIR in West Virginia, Ohio, and Pennsylvania will likely improve the quality of precipitation in the watershed. For the modeling, the wet atmospheric deposition was represented as the input of ionic species through precipitation events. The dry deposition was assumed to be included implicitly in the loads being generated at the surface.

Both anthropogenic and naturally-existing chemicals can be observed at the land surface. The mass of these chemicals can be time-variant depending on the source of the chemicals, the chemical evolution paths, source minerals, and past runoff patterns. The time variable loadings functionality of the model can be applied to simulate these sources through MDAS hydrologic components and chemical concentrations of the sources.

As percolation/evapotranspiration occurs during and after the rainfall event, the moisture conditions of the subsurface zone are constantly updated. Due to the transient nature of the subsurface hydrology, the associated chemical loadings from these zones should also display time-variant characteristics. All of the chemical loadings from different flow domains (surface and subsurface) will contribute to the water quality conditions in the stream reach and be subjected to further chemical reactions within the reach. The land components for MDAS are shown in **Figure 5-1**.

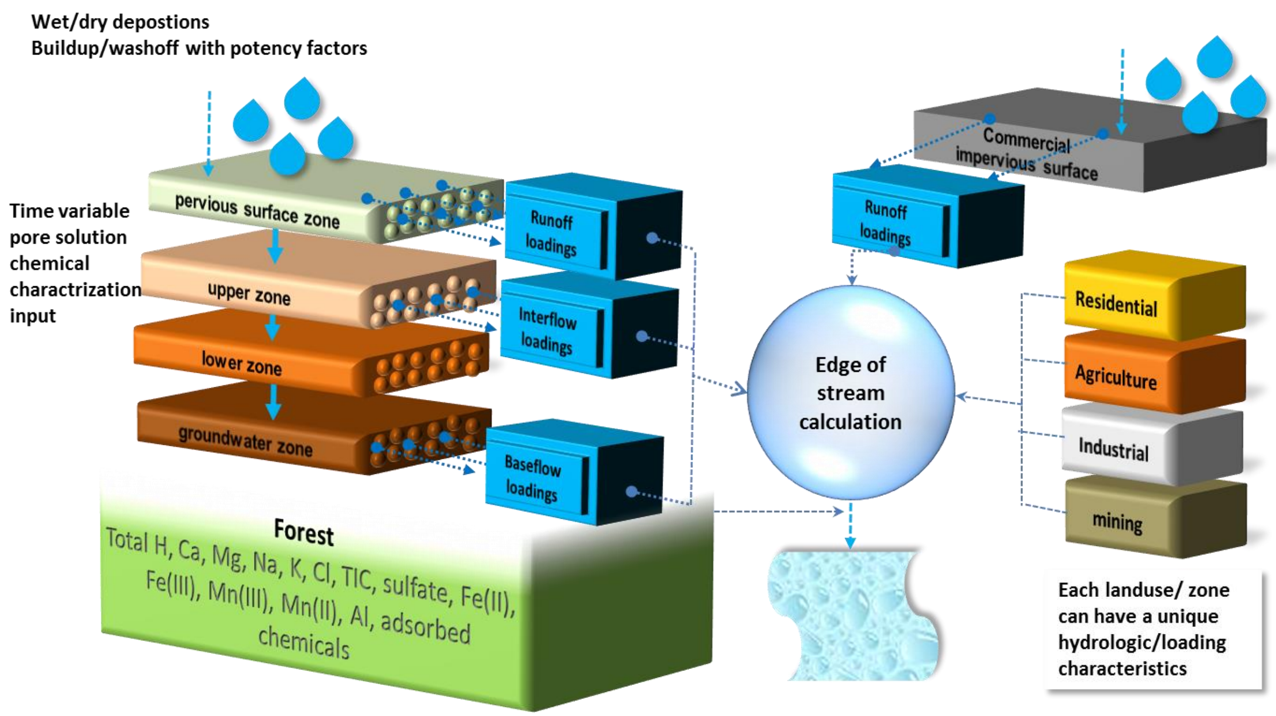


Figure 5-1. Land components of the LSPC-MDAS model

5.3 Land Sources in the Meadow River pH MDAS Model

5.3.3 Atmospheric Deposition and Background Loadings

Atmospheric depositions were considered as a source that could alter the background chemical and acidity loadings. The acidity is primarily formed from nitrogen dioxides and sulfur dioxide, which enter the atmosphere through exhaust and smoke from burning fossil fuels such as gas, oil, and coal.

Weekly wet/dry deposition data for years 2000-2014 were retrieved from the national atmospheric deposition program’s station WV18/PAR107-parsons in Tucker County. The Clean Air Status and Trends Network (CASTNET) was also accessed to retrieve dry deposition data. Dry deposition of major chemical components pertinent to MDAS modeling was implicitly included as a part of surface loadings. Weekly wet deposition data were retrieved from the same source. Wet deposition concentrations were assigned to precipitation events.

In soils, acidity-controlling parameters such as base saturation, cation exchange capacity, dissolution susceptibility of aluminum minerals (aluminum hydroxides), and soil carbon dioxide are known to influence acidification of the soils and land outflows. During the calibration, model soil parameters were refined within literature value ranges by comparing the simulated results with instream background water quality data. The selected background data were based on absence of AML, seeps or dosing applications to eliminate contaminant or human influences to the data. Model calibration aimed to replicate the relationship between atmospheric deposition and soil conditions that together produce instream conditions.

5.4 Overview of Stream Components in the pH MDAS Model

The stream components in MDAS include the dominant processes regulating the interactions and transport of major ions, metals, adsorbing materials, and mineral phases. Reactions between the water column and the streambed are represented along with the reactions governing the distribution of dissolved and particulate chemicals.

5.4.1 Water Column

The chemical loadings from the land were transported to the adjacent stream reach via the hydrologic functionalities in LSPC. The in-stream hydraulic transport was simulated in LSPC based on the complete-mix, unidirectional flow concept and kinematic wave flow routing method. MDAS's geochemical reactions within the channel are based on thermodynamics and chemical kinetics. The foundation of MINTEQA2/MINEQL is an equilibrium calculation for the major reactions that define the chemical composition of the stream reach during a given time step. Most speciation reactions are fast relative to the time step and the equilibrium assumption is reasonable. However, for certain reactions, such as the oxidation of ferrous iron to ferric iron or the adsorption of metals on iron oxyhydroxides, reactions may be limited by the kinetics, and not necessarily reach equilibrium. The major limitation of the equilibrium approach is mitigated by incorporating simultaneous equilibrium and kinetic (non-equilibrium) calculations within the same computational time step, leading to more precise spatial and temporal representations of non-equilibrium solution conditions for certain processes. To simulate and attain realistic stream chemical conditions, the model includes a variety of chemical reactions to support various stream conditions affected by anthropogenic or natural sources:

- Chemical speciation, including trace metals
- Acid/base chemical reactions and pH simulations
- CO_2 gas degassing/ingassing kinetics in rivers and lakes
- Redox kinetics including potential photoreduction/microbial oxidation
- Kinetic mineral precipitation/dissolution
- Adsorption/desorption based on diffuse double layer (DDL) modeling
- Cation adsorption/desorption on clay surfaces represented by cation exchange capacity
- Aging/burial of active/inactive sediment layers related to sediment deposition from the water column and scour from the stream bed

The precipitation/dissolution and the adsorption/desorption reactions both occur in the water column and streambed sediments. The heat loading into the stream from land and point sources is also considered and can be simulated. The resulting stream temperature is used for all temperature-dependent chemical reactions occurring within the stream. The stream components represented in MDAS are shown in **Figure 5-2**.

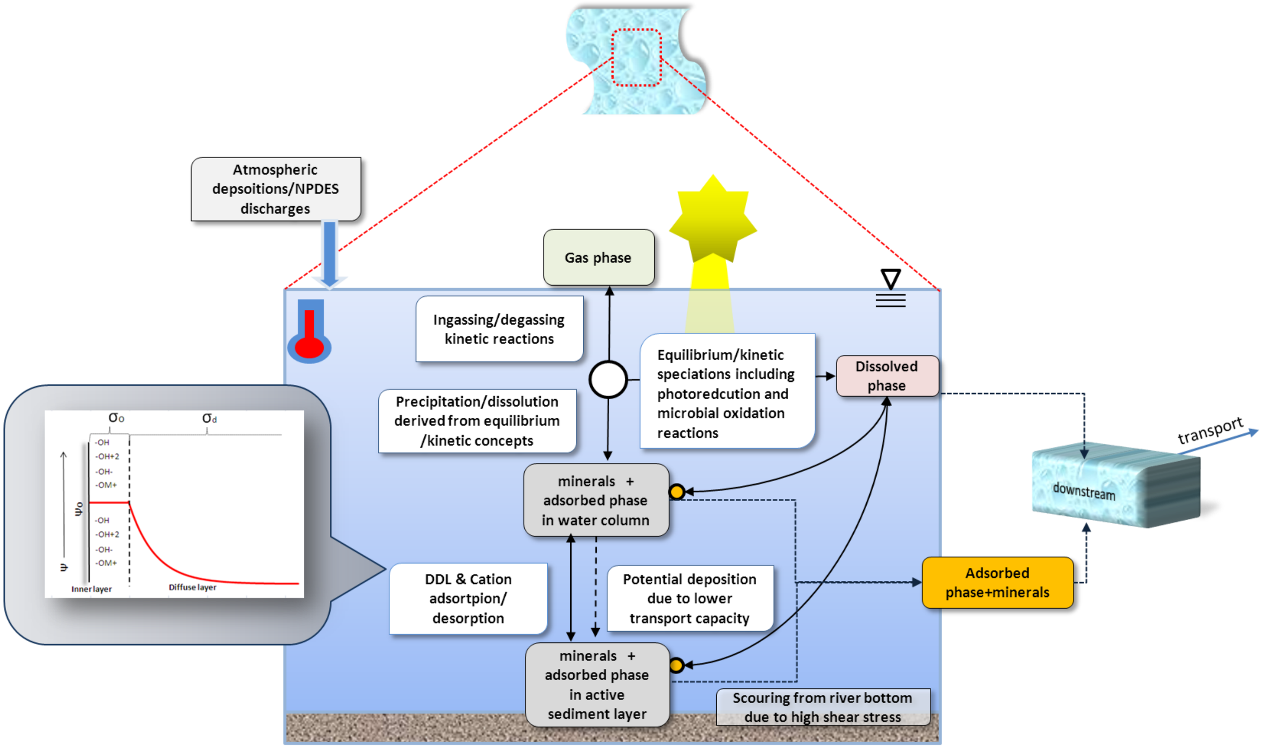


Figure 5-2. Stream components in MDAS

5.4.2 Aqueous Speciation Model in MDAS

The solution to the model equations for the reactions specified in MDAS is based on the MINTEQA2/MINEQL models with the thermodynamic database based on the MINTEQA2, Version 4.0 database. The concepts and thermodynamic data for the diffuse double layer (DDL) model for hydrous ferric oxide are based on a study conducted by Dzombak and Morel (1990). Research conducted by Tonkina, et al. (2003) and Karamalidis and Dzombak (2010) for adsorption on hydrous manganese oxide and gibbsite was reviewed and the results were incorporated into the MDAS DDL model data. **Table 5-1** shows all significant chemical species, other than the free ions, currently included in MDAS database for a chemical system based on major ions, aluminum, iron, and manganese, and adsorption/desorption to oxides and clays. A smaller subset of chemical components were examined in Meadow River to assess the pollutant contributions.

Table 5-1. Chemical components and complexes available in MDAS.

Components	Aqueous Species		Adsorbed Species		Solids
H^+	H^+	$Fe(OH)_2^+$	$:FehO^-$	:FehOBe+	Iron
Ca^{+2}	Na^+	$Fe(OH)_3$ (aq)	$:FehOH_2^+$	:FeOBe+	Aluminum
CO_3^{-2}	K^+	$Fe(OH)_4^-$	$:FehOHCa^{+2}$	KX	Manganese

Components	Aqueous Species		Adsorbed Species		Solids
Fe^{+3}	Ca^{+2}	$Fe_2(OH)_2^{+4}$	$:FehOHSO_4^{-2}$	CaX_2	Calcite
Fe^{+2}	Mg^{+2}	$Fe_3(OH)_4^{+5}$	$:FehSO_4^-$	MgX_2	Gypsum
Mn^{+2}	Al^{+3}	$FeSO_4^+$	$:FehOMn^+$	AlX_3	Jurbanite
Mn^{+3}	Fe^{+2}	$Fe(SO_4)_2^-$	$:FehO(FeII)^+$	FeX_2	-
Al^{+3}	Fe^{+3}	$FeCl^{+2}$	$:FehCO_3^-$	MnX_2	-
SO_4^{-2}	Mn^{+2}	KCl (aq)	$:FehCO_3H$	-	-
H_2O	Mn^{+3}	KOH (aq)	$:FeO^-$	-	-
Na^+	SO_4^{-2}	KSO_4^-	$:FeOH_2^+$	-	-
K^+	Cl^-	$MgCl^+$	$:FeOCa^+$	-	-
Mg^{+2}	CO_3^{-2}	$MgOH^+$	$:FeOMg^+$	-	-
Cl^-	$AlOH^{+2}$	$MgSO_4$ (aq)	$:FeOHSO_4^{-2}$	-	-
Be^{+2}	$Al(OH)_2^+$	$MgCO_3$ (aq)	$:FeSO_4^-$	-	-
FeOH(s)	$Al(OH)_3$ (aq)	$MgHCO_3^+$	$:FeOMn^+$	-	-
FehOH (s)	$Al(OH)_4^-$	$MnOH^+$	$:FeO(FeII)^+$	-	-
AlOH (s)	$Al_2(OH)_2^{+4}$	$Mn(OH)_4^{-2}$	:FeO(FeII)OH	-	-
MnOH (s)	$Al_3(OH)_4^{+5}$	$Mn_2(OH)_3^+$	$:FeCO_3^-$	-	-
MnhOH (s)	AlCl+2	Mn_2OH^{+3}	$:FeCO_3H$	-	-
X^-	AlSO4+	$MnSO_4$ (aq)	$:AlO^-$	-	-
-	Al(SO4)2-	$MnCl^+$	$:AlOH_2^+$	-	-
-	$Be(OH)_2$	$MnCl_2$ (aq)	$:AlOCa^+$	-	-
-	CaOH+	$MnCl_3^-$	$:AlOHSO_4^{-2}$	-	-
-	CaSO4 (aq)	$MnCO_3$ (aq)	$:AlSO_4^-$	-	-
-	CaCl+	$MnHCO_3^+$	$:AlOFe^+$	-	-
-	CaCO3 (aq)	NaCl (aq)	$:AlOMn^+$	-	-
-	CaHCO3+	NaOH (aq)	$:MnO^-$	-	-
-	FeOH+	$NaSO_4^-$	$:MnOCa^+$	-	-
-	Fe(OH)2 (aq)	$NaCO_3^-$	$:MnOMg^+$	-	-
-	Fe(OH)3-	$NaHCO_3$ (aq)	:MnOMgOH	-	-
-	FeSO4 (aq)	HSO_4^-	$:MnOMn^+$	-	-
-	FeCl+	$H_2CO_3^*$ (aq)	:MnOMnOH	-	-
-	FeHCO3+	HCO_3^-	$:MnhO^-$	-	-
-	FeOH+2	OH^-	NaX	-	-

Notes: 'h' indicates a high affinity site for chemical adsorption. Species with the same combination of components but no 'h' have a low affinity site. In reality, species with and without the 'h' are physically identical, but the designation is applied within the model to explain observed adsorption behavior.

'X' indicates a clay adsorption site.

':' indicates an adsorption surface provided by metals (Fe: hydrous ferric oxide, Al: gibbsite, Mn: hydrous manganese oxide).

5.4.3 Streambed and Suspended Sediment

The streambed was configured to contain two virtual model layers in MDAS. The first layer in the model was represented as an active sediment layer that participates in all chemical reactions. The second modeled layer was represented as a non-active sediment layer but contributes to total sediment and mineral mass. The active layer was thought to be either freshly precipitated minerals or shallow sediment layer that reacts with chemicals/minerals in the overlaying water within the modeled computational time step. The non-active layer was assumed to be aged and has lost chemical reactivity. Both layers were subjected to sediment aging and/or burial. The model sediments were represented by sand (as non-cohesive sediment), and silt and clay sized minerals (as cohesive sediment). Clay size minerals included clay, calcite, gypsum, jurbanite, and others that could potentially be present in acidic/post-remedial-solution discharges from pollutant sources. Metal oxides and clay layers provided surface areas for cations and anions to adsorb and desorb based on the DDL model.

Deposition to and scour from the streambed sediments were simulated on both the active and the non-active layer in the stream channel, with full simulated transport with adsorbed chemicals. The exchange between the water column and the streambed of clay, metal oxides, and other minerals was determined in the model based on the shear stress at the sediment surface layer and the hydrogeometry conditions of each reach.

5.4.4 Kinetics Representations in MDAS

While the equilibrium approach is suitable for many of the reactions in the model, additional non-equilibrium processes and reactions are represented by kinetic formulations in order to provide a greater accuracy in the stream environment. Kinetics are applied to the following in the model:

- Degassing/ingassing of CO_2
- Calcite dissolution and precipitation
- Metal oxides, gypsum and jurbanite dissolution and precipitation
- Metals oxidation/reduction
- Aging/burial of active sediment layer

5.5 MDAS Instream Model Schematic

The model schematic (**Figure 5-3**) illustrates the MDAS model functionality, in other words, how MDAS subroutines and chemical constituents interact with each other. The numbers in the figure correspond with the numbered steps below.

1) The chemical constituents land input will be processed through the edge-of-stream calculation to generate chemical and total hydrogen loadings. The assigned chemical concentrations will be distributed into Dissolved Chemical *C-comp(W)* and Particulate Chemical *C-comp(w-ads)*. The user-assigned *minerals (w)* will provide an adsorption surface in the calculation to estimate the *C-comp(ads-w)* value. No kinetics calculation will be performed at this level.

2) Dissolved/adsorbed chemicals and minerals will go through advection transport via LSPC function, depending on flow conditions and the physical characteristics of the minerals.

3) Some of the minerals will stay in the same reach for the next time step depending on the flow conditions.

4) After minerals are subjected to the advection transport, LSPC applies the BEDEXCHANGE subroutine*)* and redistributes them as suspended *minerals (W)* and sedimentary *minerals (S)* in the river bed.

5) Subroutine ADVQAL in LSPC will inherit the minerals' advection and bed-exchange information derived through ADVECT and BEDEXCHANGE and apply the results to generate suspended adsorbed *C-comp(w-ads)* and sedimentary adsorbed *C-comp(S-ads)*. As a result, some portion of *C-comp(w-ads)* will be transported to the downstream reach, and there will be exchange between *C-comp(w-ads)* and *C-comp(s-ads)* based on the minerals' behavior.

6) Next, the stream components within *C-comp (W)*; *minerals (W)* and *(S)*; and *C-comp (w-ads)* and *(S-ads)* will become inputs to the speciation model (chemical kinetics and equilibrium calculation). The model evaluates chemical components in the water column, on the suspended sediments, and on the streambed exposed to overlaying water. Active sediment layer and non-active sediment layer are controlled by both MDAS and LSPC models.

7) The speciation model performs the re-distribution of the chemical components, and the stream composition is updated. Some of the minerals can be either precipitated or dissolved depending on the solution condition.

8) The results will stay in the reach segment and will be subject to renewed transport and reactions once new loadings from point sources, landuse activities, and atmospheric sources are added to them for the next time step.

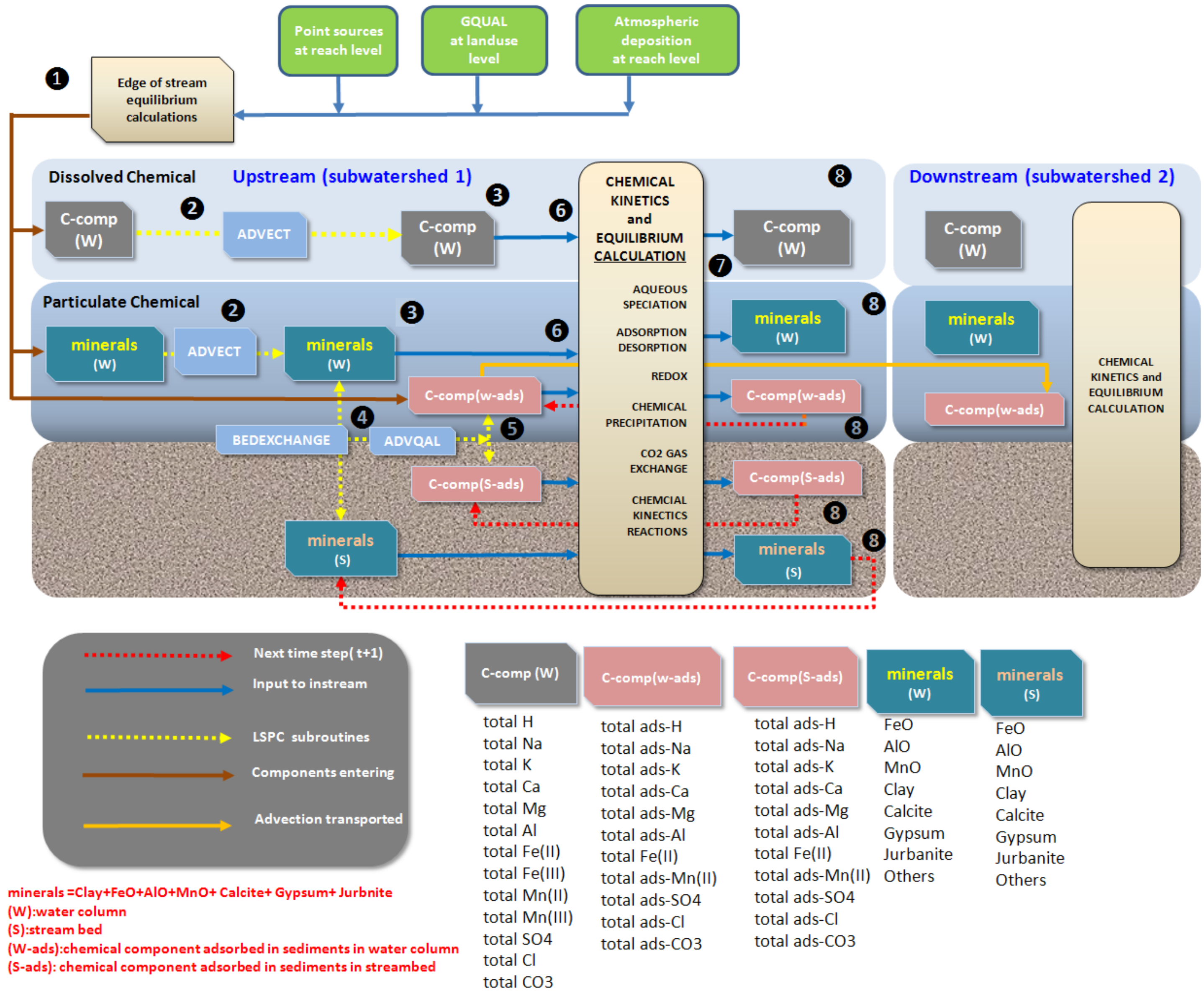


Figure 5-3. MDAS module schematic and linkages

5.6 Instream Sources and Sinks Controlling Pollutant Fate and Transport

All the loadings from the previously described upland loading sources and instream chemical reactions were considered during the model calibration. The upland loadings were discharged to the stream via the hydrologic functionalities of the model. All added loadings were subjected to subsequent instream chemical reactions previously described. Major instream reactions controlling instream pH in impaired streams in the Meadow River basin include:

- Mineral precipitation
- Stream flow in relation to reaction time
- Stream buffering capacity
- Deposition of sediments due to low velocity stream conditions

Even though dissolved aluminum was not identified as an impaired parameter in these streams, instream dissolved Al concentrations were evaluated for model calibration. The model calibration identified that the instream dissolved aluminum/pH conditions were mostly influenced by mineral precipitation as a result of mixing acidic loadings with loadings from surrounding watersheds. The model also indicated that availability of the stream buffering capacity to counteract hydrogen acidity from the precipitation reactions was critical to regulate the current instream dissolved Al and pH. Additionally, the travel time of the pollutants to downstream was also identified to be an important factor as it relates to the kinetic precipitation reactions and leads to the metal deposition during low flow conditions. Available buffering capacity contributed by lime dosing also affected the fate of metals and pH, and helped to improve the stream water quality conditions by raising pH and reducing dissolved Al.

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